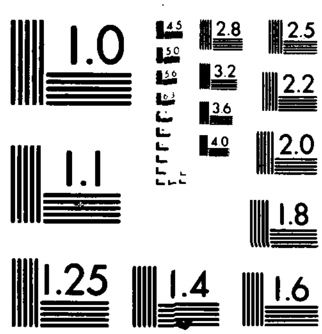
AD-A110 427 NAVAL AIR DEVELOPMENT CENTER WARMINSTER PA AIRCRAFT --ETC F/6 20/11
REVIEW OF CORROSION FATIGUE.(U)
NOV 81 E U LEE
UNCLASSIFIED NADC-81271-60 NL

1 of 1
AD A
110427

END
DATE
FILMED
2-82
DTIC



MICROCOPY RESOLUTION TEST CHART

LEVEL II

(14)

REPORT NO. NADC-81271-60

REVIEW OF CORROSION FATIGUE

E. U. Lee
Aircraft and Crew Systems Technology Directorate
NAVAL AIR DEVELOPMENT CENTER
Warminster, Pennsylvania 18974

16 DECEMBER 1981

PHASE REPORT
Work Unit No. GC129/R02208

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

Prepared for
NAVAL AIR SYSTEMS COMMAND
Washington, D.C. 20361

N O T I C E S

REPORT NUMBERING SYSTEM - The numbering of technical project reports issued by the Naval Air Development Center is arranged for specific identification purposes. Each number consists of the Center acronym, the calendar year in which the number was assigned, the sequence number of the report within the specific calendar year, and the official 2-digit correspondence code of the Command Office or the Functional Directorate responsible for the report. For example: Report No. NADC-78015-20 indicates the fifteenth Center report for the year 1978, and prepared by the Systems Directorate. The numerical codes are as follows:

CODE	OFFICE OR DIRECTORATE
00	Commander, Naval Air Development Center
01	Technical Director, Naval Air Development Center
02	Comptroller
10	Directorate Command Projects
20	Systems Directorate
30	Sensors & Avionics Technology Directorate
40	Communication & Navigation Technology Directorate
50	Software Computer Directorate
60	Aircraft & Crew Systems Technology Directorate
70	Planning Assessment Resources
80	Engineering Support Group

PRODUCT ENDORSEMENT - The discussion or instructions concerning commercial products herein do not constitute an endorsement by the Government nor do they convey or imply the license or right to use such products.

APPROVED BY: J. R. Woods
J. R. WOODS
COMMANDER, USN

DATE: 1/8/82

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER NADC-81271-60	2. GOVT ACCESSION NO. AD-A110 427	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Review of Corrosion Fatigue		5. TYPE OF REPORT & PERIOD COVERED Phase Report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) E. U. Lee		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Aircraft and Crew System Technology Directorate Naval Air Development Center Warminster, Pennsylvania 18974		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Work Unit GC129/R02208 (16)
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Air Development Center Warminster, Pennsylvania, 18974		12. REPORT DATE 16 November 1981
		13. NUMBER OF PAGES 38
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release; Distribution Unlimited (12) 113

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Corrosion Fatigue	Hydrogen Embrittlement
Stress Corrosion	Corrosive Environment
Stress Intensity Factor	Fracture Mechanics

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The work on corrosion fatigue by a number of investigators is reviewed, and the current understanding of this phenomenon is discussed. Corrosion fatigue behavior can be grouped into three types, and it is affected by numerous variables - environmental, mechanical, and metallurgical. There are several models for corrosion fatigue crack growth, which incorporate the fatigue crack growth in an inert reference environment, the sustained load crack growth, and the loading variables. The proposed mechanisms for corrosion fatigue phenomenon are pitting, metal dissolution, protective film rupture, surface energy reduction, and hydrogen embrittlement. Hydrogen embrittlement is regarded as the most influential mechanism.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-LF-014-6601

UNCLASSIFIED 393532

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

TABLE OF CONTENTS

LIST OF SYMBOLS

a	crack length
C	constant in Paris equation
C_1 and C_2	constants in Nakasa equation
da/dN	rate of fatigue crack growth
da/dt	rate of stress corrosion crack growth
$D(t)$	constant, indicating a measure of corrosion fatigue susceptibility of a material, in Barsom equation
f	cyclic loading frequency
K	stress intensity factor
K_c	critical stress intensity factor for Mode I cracks (plane stress fracture toughness)
K_D	static stress intensity factor in Nakasa equation
K_{IC}	critical stress intensity factor for Mode I cracks (plane strain fracture toughness)
K_{ISCC}	threshold stress intensity factor for stress corrosion cracking
K_m	mean value of K
K_{max}	maximum stress intensity factor
m	constant in Paris equation
m_1, m_2	constants in Nakasa equation
N	number of loading cycles
n	constant in Barsom equation
R	stress ratio
t, t_1, and t_2	loading times
t_2-t_1	loading period
ΔK	stress intensity factor range
ΔK_{th}	threshold cyclic stress intensity factor range

LIST OF SYMBOLS (continued)

α, β . . . . coefficients in Nakasa equation

γ . . . . exponent in Saff equation

τ . . . . period of one fatigue loading cycle

σ_{max} . . . . maximum stress

$\Delta\sigma$ . . . . cyclic stress range

LIST OF FIGURES

ABSTRACT

The work on corrosion fatigue by a number of investigators is reviewed, and the current understanding of this phenomenon is discussed.

Corrosion fatigue behavior can be grouped into three types, and it is affected by numerous variables - environmental, mechanical, and metallurgical. There are several models for corrosion fatigue crack growth, which incorporate the fatigue crack growth in an inert reference environment, the sustained load crack growth, and the loading variables. The proposed mechanisms for corrosion fatigue phenomenon are pitting, metal dissolution, protective film rupture, surface energy reduction, and hydrogen embrittlement. Hydrogen embrittlement is regarded as the most influential mechanism.

1.0 INTRODUCTION

Simultaneous exposure of a metallic material to a corrosive environment and a cyclic stress generally results in a degradation of fatigue resistance. The consequent cracking under the combined action of a corrosive environment and a cyclic stress is termed corrosion fatigue. Corrosion fatigue is one of the major causes for engineering structure failures and a matter of deep concern for engineers and scientists.

Considerable work has been concentrated on the characterization and understanding of corrosion fatigue, essential to service life prediction and failure control of engineering structures. However, they have been complicated by a number of variables and their interactions. Early studies were on tradi onal fatigue behavior resulting in S-N curves. Lately, corrosion fatigue behavior has been characterized in terms of crack growth rate within the framework of fracture mechanics.

As the initial task of the independent research project, "Corrosion Fatigue of Metallic Aircraft Structure," the corrosion fatigue behavior, the variables, the models, and the mechanisms, published in literature, have been reviewed. The review results are compiled and discussed in this report.

2.0 GENERAL BEHAVIOR OF CORROSION FATIGUE

In early pioneering studies and subsequent studies on corrosion fatigue,[1-12] the reduction of fatigue life in aggressive environments was found, and it was confirmed on a large number of metals and alloys. There have been some discussions as to the relative effect of environment on the fatigue crack initiation and growth. In a high purity aluminum,[3] about the same number of fatigue cycles was required for crack initiation in air and in vacuum, although the life-to-failure was 5 times longer in the latter. Similarly, in an 1100-H14 aluminum[13] and a 6061-T6 aluminum alloy,[9] the fatigue crack initiation was insensitive to environment, while the fatigue crack growth was accelerated. Recently, the emphasis has been put more on the fatigue crack growth, using fracture mechanics technique, than on the fatigue crack initiation. Fatigue crack growth behavior in inert and aggressive environments is understood as follows.

2.1 Fatigue Crack Growth in Inert Environment

The fatigue crack growth behavior of a metal or an alloy in an inert environment is characterized by a sigmoidal relationship with the stress intensity factor range, ΔK, and can be divided into three stages. Figure (1). The behavior in Stage I exhibits a "threshold" cyclic stress intensity factor range, ΔK_{th}, below which cracks do not grow under cyclic loadings.[14] Close to the ΔK_{th}, the fatigue crack growth may only be taking place along a part of the crack front and the measured fatigue crack growth rate is less than a lattice spacing per cycle. The fatigue crack growth rate above the ΔK_{th}, that is, in Stage II, can be represented by the following equation.[15]

$$da/dN = C\,(\Delta K)^m \quad (1)$$

where a is the crack length, N the number of loading cycles, and C and m experimental constants. In Stage III, the fatigue crack growth rate is greater than that given by Equation 1, and this stage is terminated whenever the maximum (cyclic) stress intensity factor is greater than the material's fracture toughness.

The fatigue crack growth rate, da/dN, is cycle dependent and frequency independent, only if the material is not strain rate sensitive or if the environmental effects are excluded. Under such a condition, da/dN is not affected by the loading waveform and a fatigue crack grows only during the loading part of the cycle.

2.2 Fatigue Crack Growth in Aggressive Environment

The fatigue crack growth behavior of metals and alloys in aggresive environments can be grouped into three basic types, (A, B, and C),[16] and may be discussed in relation to the stress corrosion cracking threshold, K_{ISCC}, Figure (2). Type A behavior is typified by the aluminum-water system with the environmental effect attributable to the synergistic action of fatigue and corrosion.[16,17] The environmental effect is a reduction in the apparent threshold for crack growth and an increase in the crack growth rate at a given level of stress intensity factor, K. This is lessened, as K approaches the critical value, K_c or K_{IC}, by the rate controlling transport process or other mechanical-chemical interactions. Type B behavior represents the steel-hydrogen system, and is affected by the environment enhanced sustained load crack growth.[17,18] The environmental effect is quite large above K_{ISCC}. Type C behavior characterizes a whole range of material-environment systems. It approaches Type B behavior above K_{ISCC} and Type A behavior below K_{ISCC}. The transition from one type behavior to the other is not always well defined.

3.0 CORROSION FATIGUE VARIABLES AND THEIR EFFECTS

Corrosion fatigue behavior is governed by a number of variables-environmental, mechanical, and metallurgical.[16,17,19-24] They are:

Environmental Variables

Types of environment - liquid, gas, liquid metal, etc.,
Pressure,
Temperature,
Partial pressure of damaging species in gaseous environments,
Concentration of damaging or beneficial species in aqueous or other liquid environments,
Electrochemical potential,
pH,
Viscosity of environment,
Velocity of environment, and
Coating, inhibitor etc.

Mechanical Variables

Maximum stress or stress intensity factor, σ_{max} or K_{max},
Cyclic stress or stress intensity factor range, $\Delta\sigma$ or ΔK,
Stress ratio, R,
Cyclic loading frequency, f,
Cyclic loading waveform (for constant amplitude loading),
Load interaction in variable amplitude loading,
State of stress,
Residual stress, and
Crack size and shape, and their relation to component size and geometry.

Metallurgical Variables

Alloy composition,
Distribution of alloying elements and impurities,
Grain size,
Microstructure and crystal structure,
Heat treatment,
Mechanical working,
Preferred orientation of grains, and
Mechanical properties (strength, fracture toughness, etc.)

The effects of significant variables are as follows.

3.1 Environmental Effects

Among the many environmental effects, the effects of liquid (water, salt water), gas (air, water vapor, hydrogen, other gases), pressure, and temperature are discussed.

a. Liquid

1. Water

Water is one of the principal corrosive environments accelerating the fatigue crack initiation and growth. The role of water in the fatigue crack initiation stage may involve several processes: pitting, preferential anodic dissolution, and surface energy reduction by adsorption. The increase of fatigue crack growth rate by water was noticed in aluminum alloys[17, 25-28] titanium alloys,[29-30] and steels.[31-35] In a 7075-T651 aluminum alloy,[17] the fatigue crack growth rate in distilled water was greater than that in an inert reference environment by a factor of ten at temperatures from 20 to 100°C.

2. Salt Water

Salt water and natural seawater lowered the fatigue strengths of steel, aluminum, and titanium alloys,[29,36,37] as compared to air. However, the relative effect of salt water and distilled water is not clear. Some found the effects of the two similar, while the others observed that salt water was more aggressive. The fatigue strength of 13 Cr stainless steel[38] was not influenced by distilled water but lowered significantly by 3% NaCl solution. Furthermore, as NaCl concentration was increased, the fatigue life decreased. In deaerated seawater, the fatigue resistance was comparable to that in air.[39]

The fatigue crack growth rates were accelerated by 3 ~ 3.5% NaCl solution and seawater in aluminum alloys (7,000 series),[40,41] steels (12Ni-5Cr-3Mo, HY 130, and 17-4 PH),[40,42,43] and titanium alloy (Ti-6Al-4V).[29] This effect of crack growth enhancement was greatest at low[44] and lower at intermediate ΔK levels.[45-47] Natural seawater, ASTM substitute seawater,[48] and 3.5% NaCl solution are often used interchangeably in corrosion fatigue studies. It was reported that the fatigue crack growth rates varied by as much as a factor of three among the three solutions.[49] Particularly for high strength steels, natural seawater was more aggressive than either laboratory substitute.

b. Gas

1. Air

Air is the most common service environment and has a prominent effect on the fatigue of metals and alloys. Since air contains nitrogen, oxygen, water vapor, hydrogen, CO_2, and CO, the observed effect could be due to one or more of these gases. The magnitude of the effect varies with the metal or alloy under consideration. The fatigue lives of Al-3% Mg alloy[50] and 1100-H14 aluminum[51] were 30% and 10 fold lower in air than in vacuum, respectively. As the air pressure increased, the fatigue life decreased, and the decrease was sharp at some critical pressure in several alloys.[10,52,53]

The number of stress cycles required for crack initiation in vacuum was close to that in air in 6061-T6,[9] DTD 5070A, and Al-Cu-Mg alloy,[26] pure aluminum,[51,54,55] and copper.[54] On the other hand, in Al-4% Cu alloy,[4] 1100-H4 aluminum,[56] pure aluminum,[55,57] 7075-T6 aluminum alloy,[58] and pure lead,[59] fewer stress cycles were required to initiate a crack in air than in vacuum. Although there is some discrepancy in the results of investigation, there is a general consensus that this environment clearly affects crack growth more than crack initiation. The crack growth rate was greater in air than in vacuum by 15 times in 1100-H14 aluminum[60] and by 6 times in DTD 5070A, SAP, and Al-Cu-Mg alloy.[26] Similar acceleration of crack growth was also observable in 7075 and 2024 aluminum alloys,[61,62] 4340 steel,[63] Ti-6Al-4V alloy,[64] and Inconel alloy 718.[65] Such an effect of air is more pronounced in the low ΔK region close to the threshold and decreases with increase in crack growth rate.

2. Water Vapor

Water vapor is the most influential environment in corrosion fatigue of various metals and alloys. The fatigue life in moist air was almost one-tenth of that in dry air for 2024-T3 aluminum alloy.[66] Similar decreases in fatigue life with the presence of water vapor were observed for moist air, moist argon and nitrogen, and water vapor alone.[4,6,9,13,66-69]

In several aluminum alloys (DTD 5070A, SAP, and pure aluminum),[26] the fatigue crack growth rate was increased about ten times by water vapor. In 7075 and 2219-T851 aluminum alloys,[61,70] it was higher in laboratory air, wet argon, and water vapor than in dry argon. A similar effect on fatigue crack growth was also found in steels (4340,[71,72] Ni-Cr-Mo-0.45 C, and 18Ni maraging[32]) and titanium alloys.[30]

The detrimental effect of water vapor was more pronounced with increase in yield strength[73] or decrease in fracture toughness.[74]

3. Hydrogen

Hydrogen has been known to induce embrittlement under monotonic or static loads, and to have a significant effect on fatigue of aluminum, steel, and titanium alloys. In hydrogen, the fatigue life was reduced to nearly one-third of that in air for Al-4% Cu and BS L65 alloys,[4] and sharply for Armco iron,[75] ferritic and austenitic steels,[75] and Ti-Al-Zr alloy.[76] In dry hydrogen, the fatigue crack growth rate of HY-80 steel[77] increased by a factor of 10 to 30 over that in air. Similar enhanced fatigue crack growths in hydrogen were also seen in ASME SA 105 Grade II,[78] D6AC,[79] 18Ni maraging,[33] and medium carbon steels,[80] and Ti-6Al-4V alloy.[81]

The susceptibility to the hydrogen attack increased with increase of yield strength in 4340, HY-80, A514-B, and HP 9-4-.20 steels, and it varied with the ΔK value and the microstructure of the alloy.[82,83] The deleterious effect of hydrogen on fatigue crack growth was reduced or removed by adding oxygen, air, or water vapor to the hydrogen environment.[33,84] The tendency of impurities, such as oxygen,[84,85] air,[84] or water vapor,[85] in hydrogen to retard or eliminate the effect of hydrogen on steel was also observed for statically loaded specimens. This effect has been attributed to preferential adsorption of oxygen on the crack surface at the crack tip.[84,85] The adsorbed layer of oxygen is believed to prevent hydrogen adsorption on the freshly cracked surfaces and, therefore, the entry of hydrogen into the steel.

4. Other Gases

Effects of other gases, such as oxygen, nitrogen, carbon monoxide, carbon dioxide, acetylene, methane, and nitrous oxide, and their combination with hydrogen have been investigated. In ASTM 514-B alloy, and HY-80 and HP 9-4-.20 steels,[83] the fatigue crack growth rate increased in various amounts for different gas combinations. Hydrogen was the most damaging, and the other gases such as oxygen, methane, carbon monoxide, carbon dioxide, and nitrous oxide were less aggressive individually. When hydrogen was combined with oxygen, carbon monoxide, nitrous oxide, or water vapor, the resultant effect was less than the linear summation of the individual effects. This synergistic effect is attributed to preferential adsorption of oxygen, carbon monoxide, nitrous oxide, or water vapor on crack surfaces.

The effect of oxygen has been described as increasing fatigue crack growth rate in aluminum alloys,[86,87] high strength steels,[88] and nickel base superalloys.[89] It was greater in high purity aluminum than in DTD 5070A aluminum alloy.[26,87,90] In 1100-H14 aluminum, the effect of oxygen on the fatigue life was found to be almost as large as the effect of water vapor.[91] In H-11 alloy, the partial pressures of both oxygen and water vapor, required to increase the fatigue crack growth rate, compared to vacuum, were roughly the same, as were the saturation or limiting da/dN values at high partial pressures.[92]

H_2S decreased the fatigue lives of medium carbon steels[80] to the same extent as hydrogen, and He + 0.5% H_2S enhanced the fatigue crack growth in Inconel alloy 718.[65] Dry SO_2 showed no effect on the fatigue of mild steel, high strength steel, and 18-8 stainless steel,[93] but He + 5.0% SO_2 accelerated the fatigue crack growth in Inconel alloy 718.[65] The fatigue crack growth rate in titanium alloys[94] was increased by, in the order, dry argon, normal air, distilled water, and aqueous 3.5% NaCl solution. This effect could be due to increasing amount of hydrogen available at the crack tip in each environment. Argon, nitrogen, and the other inert gases have been universally recognized as having no effect when dry, and having an effect similar to wet air at a corresponding partial pressure of moisture in vacuum.[26]

c. Pressure

Gas pressure is an important factor in corrosion fatigue, since a higher pressure results in a larger number of gas molecules available for reaction at gas-metal interface. Generally, the fatigue life of a metal or an alloy is reduced by increasing the pressure of an aggressive gas. As the air pressure increased, the fatigue life decreased sharply at some critical pressure in Al-3% Mg alloy[50] and several other alloys.[10,52,53] A hydrogen atmosphere of 10,000 psi reduced the fatigue life of ASTM A-302 steel, but did not affect AISI 310 stainless steel.[95]

In water vapor, the fatigue life and crack growth rate were virtually unaffected until a threshold pressure (e.g., 10^{-3} torr for aluminum alloys[96]) was reached,[6,26,68,69,86,96] then the fatigue crack growth rate increased rapidly with pressure, and it finally reached a plateau at a critical pressure.[32,35] The threshold pressure was sensitive to the loading frequency[26] (e.g., a two decade reduction in pressure with a reduction of frequency from 100 to 1 cps in aluminum alloy[17]) and the critical pressure to the stress ratio.[97] In oxygen, the presence of a threshold pressure was also observed for 316 stainless steel.[98] However, in hydrogen, the fatigue crack growth rate increased continuously with increasing pressure without reaching a plateau in high strength steel,[88] Ni-200,[99] and 75A Ti and Ti-6Al-4V alloy.[96] This indicates the absence of any saturation effect or any critical pressure of hydrogen. In Ni-200,[99] the increase of fatigue crack growth rate started at 1 torr and continued up to 150 torr. On the other hand, in the same hydrogen pressure range, the fatigue crack growth rate did not increase in 2024-T6 aluminum alloy and copper base alloy, NARloy-Z.[96]

d. Temperature

Since temperature affects the kinetics of chemical reaction, diffusion, and crack growth, its effect on corrosion fatigue crack growth, including the threshold, have been studied extensively in various alloys.[25,75,81,83,100-106]

The fatigue crack growth rate in aluminum alloys increased with increasing temperature at a given stress intensity level in a dehumidified inert reference environment and in oxygen, hydrogen, and water.[25] For a stress intensity range, ΔK, of 20 ksi $\sqrt{in}$, the corrosion fatigue crack growth rate of 4340 steel increased by a factor of 30 for a temperature increase of 70°C in distilled water.[100] Similarly, the fatigue crack growth in a metastable austenitic steel was enhanced by temperature increase at a given ΔK value in distilled water,[101] and its activation energy was found to be 8,500 cal/mol. (The activation energy for hydrogen diffusion in iron was measured to be 3,000 ~ 8,000 cal/mol.[107]). On the other hand, in hydrogen atmosphere, the fatigue crack growth rate in Ni-200[102] reached a peak at 0°C, and that in Ti-6Al-4V alloy[81] was markedly accelerated at temperatures below 0°F. At or near room temperature, the detrimental hydrogen effects on fatigue reached a maximum, and decreased with decrease or increase of temperature in Armco iron,[75] HP 9-4-.20 steel,[83] and 4130 steel.[103] At temperatures above 200°C, the hydrogen effect was absent. On the other hand, oxygen has an increasing effect with a rise in temperature.[108,109] These results suggest that the fatigue crack growth depends on temperature in both inert and aggressive environments. The temperature dependence is a function of stress intensity factor K or its range Δk, and it is related to the deformation properties of the material and the environment-metal interactions.

The threshold fatigue crack growth behavior of mild steel did not change between the ambient temperature and 300°C in air at low stress ratio, R, whereas the threshold stress intensity range, ΔK_{th}, was higher at 300°C and high R values.[105] Conversely, in A533 and A508 steels, ΔK_{th} was quite sensitive to temperature at low R values but insensitive over the temperature range ambient to 350°C at high R values. However, over the temperature range 20 to 700°C, ΔK_{th} for 316 stainless steel increased with temperature in air but remained constant in vacuum and helium.[106] This result implies that the temperature effect on near threshold fatigue crack growth behavior is primarily a function of environmental reaction in this steel.

3.2 Mechanical Effects

Among the various mechanical effects, the effects of loading frequency, load waveform, stress ratio, stress intensity factor, and load interaction in variable amplitude loading are discussed.

a. Loading Frequency

The effect of loading frequency on fatigue crack growth in inert and aggressive environments has been studied by a number of investigators.[4,20,26-28,42,43,86,87,90,110-119] Their results show that the environmental effects on fatigue crack growth are greater at lower frequencies where the corrosive environment has more time to react with the material. The frequency effect varies with the type of corrosive environment, its concentration, and the material susceptibility, and it is developed more at lower stress intensities. Some of the significant findings are as follows.

Bradshaw and Wheeler[87] found that, in a vacuum, fatigue crack growth rates were insensitive to frequency changes in DTD 5070A aluminum alloy and SAP. Wei and Landes[28] detected no essential difference in fatigue crack growth rate for 7075-T6 aluminum alloy in dehumidified argon between frequencies of 5 and 143 cps. Hutin[113] also observed no frequency effect on fatigue crack growth of 4340 steel in an inert environment.

In air, Bradshaw and Wheeler[87] measured quite similar fatigue crack growth rates for DTD 5070A aluminum alloy at 1/60 and 1 Hz but reduced one at 100 Hz. In DTD 683 aluminum alloy, the environmental frequency effect was close to that in DTD 5070A aluminum alloy with a marginal further increase in fatigue crack growth rate at 1/60 Hz. By lowering the frequency from 57 to 0.4 cps, Hartman[114] reduced the number of fatigue cycles 40% to grow a crack from 1.5 to 25mm for 2024-T3 aluminum alloy and 30% for 7075-T6 aluminum alloy in a saturated water vapor. The frequency dependent fatigue crack growth behavior of these two aluminum alloys was confirmed by Krupp,[120] who tested in 100% RH air at frequencies of 24 and 3,400 cpm. Gallagher[115] and Pao[116] studied the corrosion fatigue behavior of 4340 steel at various frequencies in distilled water and water vapor, respectively. Their data, some of which are illustrated in Figure (3), clearly indicate that the aggressive environments enhance the fatigue crack growth more at lower frequencies. They are consistent with the results of Barsom[42,43] on 12Ni-5Cr-3Mo maraging steel tested in a 3% NaCl solution, those of Gallagher[21] on HY-80 steel tested in a 3.5% NaCl solution, those of Miller[117] on a low alloy steel tested in distilled water, and those of Hutin[113] on another low alloy steel tested in water vapor. Such frequency effects in steel, however, were observable at lower frequencies and at higher water vapor pressures (and in aqueous environments) as compared to those in aluminum alloys. This difference may be attributed to the difference in the reactivity of these alloys to water vapor/water.[118] Meyn[119] fatigue-tested Ti-8Al-1Mo-1V alloy in salt water and distilled water, and detected a strong dependence of the fatigue crack growth on the frequency, much higher at lower frequencies, in contrast to the relatively mild frequency dependence of aluminum alloys in water.

b. Load Waveform

The environmental acceleration of fatigue crack growth is strongly dependent on the load waveform in some material-environment systems.[19,43,121] In the case of steel-salt water and steel-water systems,[43] the influence of load waveform is significant, but in the case of aluminum-water system it is quite small.[19,121]

Barsom[43] studied the effect of load waveform on fatigue crack growth in 12Ni-5Cr-3Mo maraging steel at K levels below K_{ISCC}. Under sinusoidal, triangular, and square waveform loadings, the fatigue crack growth rates in an air environment were identical, Figure (4). In a 3% NaCl solution, the fatigue crack growth rates under sinusoidal and triangular waveform loadings were almost identical and three times higher than those in air. On the other hand, under square and negative sawtooth waveform loadings, the fatigue crack growth rates in a 3% NaCl solution were essentially the same as those in air, Figure (5). These results indicate that the environmental effect on fatigue crack growth is operative only while the tensile stress is increasing and not during the constant load portion of each load excursion below K_{ISCC}.

c. Stress Ratio

The fatigue crack growth rate is affected by the stress ratio, R, for a given cycle of loading in inert and aggressive environments. In an aggressive environment, at a given level of the maximum stress intensity factor, K_{max}, for a large value of R, e.g., 0.8, the environmental acceleration of fatigue crack growth rate is large.[17,29,34] On the other hand, for a small value of R, e.g., 0 0.2, the environmental effect is small.[17,34,35] Studies in a wide range of steels and non-ferrous alloys, tested in ambient temperature air, indicated that as R was raised within a range from 0 to 0.9, the fatigue crack growth rate was increased and the threshold stress intensity range, K_{th}, was markedly decreased.[60,63,104-106,122-152] The R dependence on near-threshold fatigue crack growth, however, was reduced at negative R values,[153] with increasing temperature,[104] and with increasing strength in tempered martensitic steels.[122]

d. Stress Intensity Factor K

The environmental effect is pronounced at short crack lengths or low values of stress intensity factor K, and small at high K levels.[26,27] For example, in 2024-T3 aluminum alloy,[27] moisture in the environment increased the fatigue crack growth rate by a factor of ten over that in the reference environment at low K levels, but it induced only a small effect at high K levels. Such a reduction in moisture effect at high K levels was also noted in clad DTD 5070A and bare DTD 683 aluminum alloys.[26]

e. Load Interaction in Variable Amplitude Loading

Extensive investigations have been undertaken to determine the effects of load interaction in variable amplitude loading on fatigue crack growth behavior.[22,23,154-163] It has been found that the application of a single overload or a few cycles at high tensile loads results in crack retardation, that is, a decrease in the fatigue crack growth rate. However, the relationship of the crack retardation and the environmental effect has not been well understood.

Chanani[164] fatigue-tested 2024-T8, 7075-T6, and 7075-T73 aluminum alloys in laboratory air and 3.5% salt water to define the relationship of the crack retardation behavior and the environmental effect. Single overload cycles at overload ratios of 1.5, 2.0, and 2.5 were used. The single overloads were found to cause a decrease in constant amplitude crack growth in salt water, as in air. Also, the number of delay cycles increased with increase in overload ratio in salt water, as in air. However, the number of delay cycles was larger in air than in 3.5% salt water, and the difference was greater for the 7075-T6 aluminum alloy than for the 2024-T8 and 7075-T73 aluminum alloys. The results show that the greater the crack retardation in air, the larger is the environmental effect (i.e., reduction of crack retardation).

3.3 Metallurgical Effects

Among the various metallurgical effects, the effects of grain size, microstructure, and yield strength are discussed.

a. Grain Size

Though refining grain size is beneficial in raising the fatigue limit or endurance strength of a material,[165] the effect of grain size on fatigue crack growth was found to be negligible at intermediate growth rates.[165-167] At low growth rates in air, however, several workers[133,134,139,141,143,146] observed improved resistance to near-threshold crack growth with coarser grain sizes. Robinson and Beevers[143] reported an order of magnitude decrease in near-threshold growth rates in alpha-titanium after coarsening the grain size from 20 to 200 μm. Similar effects were also seen in Ti-6Al-4V alloy.[146] Furthermore, the threshold intensity range ΔK_{th} value was increased markedly in low strength steels by increasing the ferrite grain size.[133,134]

b. Microstructure

The fatigue behavior of IN 838 alloy (CuNiCr alloy) with solutionized microstructure was not affected by free corrosion in a salt solution.[168] However, the fatigue resistance of the same alloy with precipitation hardened microstructure was lowered under the identical test conditions.[168] This result indicates that the solutionized microstructure is more resistant to corrosion fatigue than the precipitation hardened one.

c. Yield Strength

In 4340 steel, the higher the yield strength, the greater was the effect of corrosive environment (3% NaCl solution) on fatigue crack growth rate, and the lower was the value of K_{ISCC}.[169] Similarly, in 300M steel, the near-threshold fatigue crack growth rate in moist air increased markedly with increasing cyclic yield strength.[122,141] In low strength steels, the ΔK_{th} value in air decreased with increasing yield strength.[128,133,134] As pointed out earlier, the susceptibility to hydrogen embrittlement was enhanced by the increase of yield strength in steels.[82,83] However, somewhat different behavior was observed in non-ferrous alloys. Small reductions in ΔK_{th} value were seen in Al-Zn-Mg[151] and aluminum-bronze alloys[152] as the cyclic yield strength was decreased.

4.0 MODELS FOR CORROSION FATIGUE CRACK GROWTH

Several models have been proposed to establish a quantitative relationship of the corrosion fatigue crack growth rate with the loading variables. Five representative ones, formulated by Wei and Landes,[18] Wei,[24] Barsom,[43] Nakasa,[170] and Saff[171] are discussed.

4.1 Wei-Landes Model

Wei and Landes[18] expressed the fatigue crack growth rate in an aggressive environment, $(da/dN)_e$, as the sum of the fatigue crack growth rate in an inert reference environment, $(da/dN)_r$, and the crack growth under sustained load in an identical aggressive environment, $\int_0^{\tau} \frac{da}{dt}[K(t)] \cdot dt$. That is

$$\left(\frac{da}{dN}\right)_e = \left(\frac{da}{dN}\right)_r + \int_0^{\tau} \frac{da}{dt}\left[\ K(t)\right] \cdot dt \qquad \ldots \quad (1)$$

where a is the crack length, N the number of fatigue loading cycles, t the time of sustained loading, and τ the period of one fatigue loading cycle. The integration of the second term is taken over one cycle of fatigue loading, and incorporates the effect of frequency and loading variables through K(t).

The predictions by this model are in good agreement with the fatigue test results of 18Ni maraging steel in hydrogen environment and those of H-11 steel in humid air.[18] This model is also applicable to the titanium-salt water system but not to the aluminum-water system.[18]

4.2 Wei's Modified Model

The above Wei-Landes model[18] is based on the premise that the aggressive environment does not affect the fatigue crack growth at K_{max} below K_{ISCC}. However, the results of other investigations showed that the fatigue crack growth rate was increased significantly by an aggressive environment at K_{max} below K_{ISCC}.[43,168,172-174] A similar result was obtained by Pao[116] and Wei,[24] who investigated the fatigue crack growth behavior of 4340 steel in dehumidified argon and in water vapor at K_{max} below K_{ISCC}. Their results clearly showed that water vapor increased the fatigue crack growth rate below K_{ISCC} and the data at different frequencies followed essentially parallel lines in log(da/dN) versus log (ΔK) coordinates, Figure (3). On the basis of this result, Wei[170] modified the Wei-Landes model[18] as follows.

For $K_{max} < K_{ISCC}$

$$\left(\frac{da}{dN}\right)_e = \left(\frac{da}{dN}\right)_r + \left(\frac{da}{dN}\right)_{cf} \qquad \ldots \quad \ldots (2)$$

where $\left(\frac{da}{dN}\right)_{cf}$ is the environment induced increase in fatigue crack growth rate.

For $K_{max} > K_{ISCC}$

$$\left(\frac{da}{dN}\right)_e = \left(\frac{da}{dN}\right)_r + \left(\frac{da}{dN}\right)_{cf} + \left(\frac{da}{dN}\right)_{scc}$$

$$= \left(\frac{da}{dN}\right)_r + \left(\frac{da}{dN}\right)_{cf} + \int_0^{\tau}\left[\frac{da}{dt}(K)\right]dt \qquad \ldots(3)$$

where $(da/dN)_{scc}$ is the contribution by sustained load crack growth.

4.3 Barsom Model

Barsom,[43] and Imhof and Barsom[169] studied the fatigue behavior of 12Ni-5Cr-3Mo maraging steel and 4340 steel in air and in 3% NaCl solution at K_{max} below K_{ISCC}. According to the results, the fatigue crack growth is independent of load waveform and frequency in air, dependent on both variables in 3% NaCl solution, and represented by the following equation.

$$\frac{da}{dN} = D(t) \cdot (\Delta K)^n \quad \ldots \qquad \ldots(4)$$

where D(t) is a measure of the corrosion fatigue susceptibility of the material, and depends on environment, load waveform, frequency, and yield stress. In air D(t) is a constant, and Equation (4) reduces to the Paris fatigue crack growth equation.[15] The value of n is 2 for the 12Ni-5Cr-3Mo maraging steel and 2.7 for the 4340 steel.

4.4 Nakasa Model

Nakasa and his coworkers[170,175] investigated the fatigue behavior of Ni-Cr-Mo martensitic steel in water, and expressed the fatigue crack growth rate as

$$\left(\frac{da}{dN}\right)_e = \alpha\left(\frac{da}{dN}\right)_r + \left(\frac{\beta}{f}\right)\cdot\left(\frac{da}{dt}\right)$$

$$= \alpha C_1 (\Delta K)^{m_1} + \beta\int_0^{\tau} C_2 [K_D]^{m_2} \cdot dt \qquad \ldots(5)$$

where C_1, C_2, m_1, and m_2 are constants, f the loading frequency, α and β the coefficients, K_D the static stress intensity factor, and τ the period of one fatigue loading cycle. The value of α was assumed to be unity, and β was determined to be $0.2 \sim 0.4$ under the test condition of $f = 55 \sim 345$ cpm and $(K_m/_{\Delta K}) = 0.5 \sim 4.0$. ($K_m$ is the mean K value). The only difference between the Wei-Landes model[18] (Equation (1)) and this model is the coefficient β in the second term.

4.5 Saff Model

Saff and Rosenfeld[171,176] studied the fatigue behaviors of 300M and HP 9-4-.30 steels in synthetic sea water under the condition of alternate immersion and drying, and modified the Wei-Landes model.[18] According to this model, for any environment, the total fatigue crack growth rate for any cycle, $(da/dN)_{total}$, is the sum of two components: one due to mechanical loading in a reference environment, $(da/dN)_r$, and one due to sustained load in an aggressive environment, $(da/dN)_{env}$.

$$\left(\frac{da}{dN}\right)_{total} = \left(\frac{da}{dN}\right)_r + \left(\frac{da}{dN}\right)_{env} \qquad \ldots \qquad (6)$$

where

$$\left(\frac{da}{dN}\right)_{env} = \int_{t_1}^{t_2} \left(\frac{da}{dt}\right)_{immersed} \cdot dt \qquad \text{(during immersion)}$$

$$\left(\frac{da}{dN}\right)_{env} = \int_{t_1}^{t_2} \left(\frac{da}{dt}\right)_{immersed} \cdot e^{-\gamma t} \cdot dt \qquad \text{(during drying)}$$

(t_2-t_1) is the loading period. During the drying cycle, the environmental acceleration decays exponentially with time, and the exponent γ is 0.00175 in the 300M steel and zero in the HP 9-4-.30 steel.

5.0 MECHANISMS OF CORROSION FATIGUE

It has been proposed that the corrosion fatigue is attributable to one or more of the following mechanisms: pitting, metal dissolution, protective film rupture, surface energy reduction, and hydrogen embrittlement.

5.1 Pitting Mechanism

Pits, somehow formed during the corrosion fatigue process, have been blamed for the premature crack initiation.[177,178] The pit formation in aggressive environments undoubtedly reduces the fatigue life. However, the corrosion fatigue also occurs without any pit formation. For example, low carbon steels are highly susceptible to corrosion fatigue in acid solutions, where pits are not observed.[39] Furthermore, according to Duquette and Uhlig,[179] corrosion pits are not responsible for the corrosion fatigue of low carbon steels in 3% NaCl solution. Therefore, it may be believed that the corrosion pits are not the cause of corrosion fatigue but rather the result.

5.2 Metal Dissolution

Strained regions, associated with persistent slip bands, cracktip, or grain boundary, are known to act as anode and the unstrained regions as cathode in an aggressive environment.[180] As the result, the strained regions are electrochemically attacked and dissolved, and cracks are initiated and/or grown.[181-184] Pyle and his coworkers[184] explain this mechanism as follows. The dynamic plastic deformation during the tensile half cycle allows localized dissolution at the step edges on the crack front. Reversed slip during the compression half cycle sharpens the crack front. Reapplication of the tensile stress then results in either further plastic deformation and dissolution or mechanical propagation by brittle fracture. It is envisaged that this cycle of yielding - dissolution - compression - mechanical propagation - yielding takes place during each stress cycle. As the crack grows, the importance of dissolution, compared to the mechanical propagation, alters. This accounts for the observation of Rollins, et al[178] that the environment becomes less important as the crack length increases.

5.3 Protective Film Rupture

Many metals are covered by oxide films when exposed to aggressive environments. Some of those films may be thick (> 10 Å), as in the case of copper or aluminum, or thin in metals showing passive behavior (e.g., stainless steel), and are cathodic to the base metal. It has been postulated that mechanical stresses rupture or fatigue slip steps break through the covering oxide film, thus exposing the small anodic regions to the large cathodic film.[185-188] Consequently, the anodic regions are dissolved and fatigue cracks are initiated prematurely. In Laute's work,[185] low frequencies extended the fatigue lives, presumably because the lower frequencies allowed film repair and reduced anodic dissolution of newly emerging metal. Simnad and Evans[189] also suggested the possibility of the protective film rupture mechanism in neutral solutions, but pointed out that in acid solutions, where oxide films are soluble, this mechanism is not valid.

5.4 Surface Energy Reduction

Liquids, adsorbing on solids, lower the surface energy of the solids and significantly change the mechanical properties, especially the resistance to fracture.[190,191] Benedicks[192] suggested that the reduction in surface energy of the solids led to a dilation of surface atomic bands and facilitated the slip process. However, steels are not susceptible to corrosion fatigue in neutral aqueous deaerated solutions, even when strongly adsorbing ions such as Cl^- are present. Moreover, in perfectly brittle materials, the releasing energy is equal to the surface energy required to generate two new surfaces of a crack. But in materials where plastic deformation occurs at the crack tip prior to fracture, the releasing energy is the sum of the surface energy and the plastic deformation energy for forming the new crack surfaces. Therefore, this surface energy reduction mechanism can not account for the corrosion fatigue phenomenon.

5.5 Hydrogen Embrittlement

From the results of previous investigations on corrosion fatigue in both ferrous and nonferrous metals, it has been speculated that an increase of fatigue crack growth rate in water or water vapor is attributable to the reaction of water molecules with crack surfaces.[26,27,32,193] The related mechanism[116] has been proposed as follows. Water or water vapor is chemisorbed on the freshly produced crack surfaces, and water molecules undergo dissociative chemical reaction to release hydrogen. The amount of hydrogen produced depends on the time allowed for this chemical reaction to take place during each fatigue cycle and on the extent of available fresh crack surfaces. All or a part of the hydrogen generated diffuses into the metal and is expected to segregate to the region of high triaxial tensile stress near the crack tip. This hydrogen segregation embrittles the region and enhances crack growth by one or more of the hydrogen embrittlement mechanisms.[191,194-200] On each loading cycle, the crack extends, in one step, through a fraction of this hydrogen embrittled region. Following this increment of crack length, a new embrittled region is established ahead of the new crack tip through reactions of water molecules with the freshly created crack surfaces, hydrogen diffusion, and segregation. The size of hydrogen embrittled region and the hydrogen concentration within this region are greater for a longer exposure time or at a lower frequency.

A number of investigators have attributed the water or water vapor environment enhanced fatigue crack growths in aluminum alloys,[4,26,27] steels,[43,74,116,201-203] and titanium alloys[74] to the hydrogen embrittlement.

6.0 SUMMARY

The development in understanding of corrosion fatigue phenomenon has been reviewed to learn the past and current state of the art. The acquired knowledge will be applied to implement the independent research program, "Corrosion Fatigue of Metallic Aircraft Structure," and will be related to the Navy's aircraft problems originated from aggressive service environments, including salt water.

The behavior, the variables, the models, and the mechanisms of corrosion fatigue in metals and alloys, published in literature, have been studied and discussed.

Corrosion fatigue behavior can be grouped into three basic types - A, B, and C. Type A represents the aluminum-water system, where the environmental effect results from the synergistic actions of fatigue and corrosion. Type B represents the steel-hydrogen system, where there is a substantial environment enhanced sustained load crack growth. Type C falls between the types A and B, and exhibits the type A below K_{ISCC} and the type B above K_{ISCC}.

A number of variables, environmental, mechanical, and metallurgical, affect fatigue behavior. Among these variables, water, salt water, air, water vapor, hydrogen, gas pressure, temperature, loading frequency, load waveform, stress ratio, stress intensity factor, grain size, microstructure, and yield strength impose significant effects.

The representative models for corrosion fatigue crack growth are:

a. Wei-Landes Model

$$\left(\frac{da}{dN}\right)_e = \left(\frac{da}{dN}\right)_r + \int_o^{\tau} \frac{da}{dt}\left[\, K(t)\right] \cdot dt$$

b. Wei's Modified Model

$$\text{For } K_{max} < K_{ISCC} : \left(\frac{da}{dN}\right)_e = \left(\frac{da}{dN}\right)_r + \left(\frac{da}{dN}\right)_{cf}$$

$$\text{For } K_{max} > K_{ISCC} : \left(\frac{da}{dN}\right)_e = \left(\frac{da}{dN}\right)_r + \left(\frac{da}{dN}\right)_{cf} + \left(\frac{da}{dN}\right)_{scc}$$

c. Barsom Model

$$\frac{da}{dN} = D(t) \cdot (\Delta K)^n$$

d. Nakasa Model

$$\left(\frac{da}{dN}\right)_e = \alpha\left(\frac{da}{dN}\right)_r + \left(\frac{\beta}{f}\right)\cdot\left(\frac{da}{dt}\right)$$

e. Saff Model

$$\left(\frac{da}{dN}\right)_{total} = \left(\frac{da}{dN}\right)_r + \left(\frac{da}{dN}\right)_{env}$$

The proposed mechanisms, one or more of which are responsible for corrosion fatigue, are pitting, metal dissolution, protective film rupture, surface energy reduction, and hydrogen embrittlement.

From this review, the complex nature of corrosion fatigue phenomenon and its detrimental effect on integrity of aircraft and other engineering structures are well recognizable. It is essential to find the key information for effective control of corrosion fatigue in aircraft structures through further research.

REFERENCES

1. Haigh, B. P., J. Inst. Metals, Vol. 18, 1917, p. 55.

2. Gough, H. J. and Sopwith, D. G., J. Inst. Metals, Vol. 49, 1932, p. 93.

3. Wadsworth, N.J., and Hutchings, H., Phil. Mag., Vol. 3, 1959, p. 1154.

4. Broom, T. and Nicholson, A., J. Inst. Metals, Vol. 89, 1960, p. 183.

5. Bennett, J. A., in Fatigue of Aircraft Structures - *Proceedings of the* Paris Symposium (1961), Ed. Barrois, W. and Ripley, E. L.

6. Ham, J. L. and Reichenbach, G. S. in Symposium on Materials for Aircraft, Missile, and Space Vehicle, ASTM STP 345, American Society for Testing and Materials, 1962, p. 3.

7. Jenkins, G. A. and Roberts, W. T., The Atmospheric Corrosion Fatigue and Stress Corrosion Properties of Commercial High Strength Aluminum Alloy Extrusion, S and T Memo 14/62, Min. of Aviation (Great Britain).

8. Kramer, J. R. and Podlaseck, G. E., Behavior of Metals in Vacuum, Martin Co. Res. Memorandum 102, October, 1961.

9. Bennett, J. A., J. Res., Nat. Bur. Std., Vol. 68C, 1964, p. 91.

10. Achter, M. R., Danek, G. J., Jr., and Smith, H. H., Trans. Met. Soc. AIME, Vol. 227, 1963, p. 1296.

11. Bennett, J. A., Acta Met., Vol. 11, 1963, p. 799.

12. Laird, C., and Smith, G. C., Phil. Mag., Vol. 8, 1963, p. 1945.

13. Hordon, M. J., Wright, M. A., and Reed, M. E., NASA-CR-82446, National Aeronautics and Space Administration, August 4, 1965.

14. Paris, P. C., Schmidt, R. A., and Weiss, W. L., "Very Slow Fatigue Crack Growth Rates in a Steel," Presented at the Third National Symposium on Fracture Mechanics, Lehigh University, Bethlehem, PA., August, 1969.

15. Paris, P. C. and Erdogan, F., J. Basic Eng., Trans. ASME, Ser. D., Vol. 85, 1963, p. 528.

16. McEvily, A. J. and Wei, R. P., in Corrosion Fatigue: Chemistry, Mechanics and Microstructure, NACE-2, National Association of Corrosion Engineers, 1972, p. 381.

17. Wei, R. P., Eng. Fract. Mech., Vol. 1, 1970, p. 633.

18. Wei, R. P. and Landes, J. D., Mat. Res. and Std., American Society for Testing and Materials, Vol. 9, 1969, p. 25.

19. Wei, R. P. and Speidel, M. O., in Corrosion Fatigue: Chemistry, Mechanics and Microstructure, NACE-2, National Association of Corrosion Engineers, 1972, p. 379.

20. Achter, M. R. in Fatigue Crack Propagation, ASTM STP 415, American Society for Testing and Materials, 1967, p. 181.

21. Gallagher, J. P. and Wei, R. P., in Corrosion Fatigue: Chemistry, Mechanics and Microstructure, NACE-2, National Association of Corrosion Engineers, 1972, p. 409.

22. Hudson, C. M. and Raju, K. N., NASA TN D-5702, National Aeronautics and Space Administration, 1970.

23. Schijve, J., "Fatigue Crack Propagation in Light Alloy Sheet Material and Structures," Report MP 195, National Aerospace Laboratory, Amsterdam, The Netherlands, August, 1960.

24. Wei, R. P., in Fatigue Mechanisms, ASTM STP 675, American Society for Testing and Materials, 1979, p. 816.

25. Wei, R. P., Int. J. Fract. Mech., Vol. 4, 1968, p. 159.

26. Bradshaw, F. J. and Wheeler, C., Appl. Mat. Res., Vol. 5, 1966, p. 112.

27. Hartman, A., Int. J. Fract. Mech., Vol. 1, 1965, p. 167.

28. Wei, R. P. and Landes, J. D., Int. J. Fract. Mech., Vol. 5, 1969, p. 69.

29. Speidel, M. O., Blackburn, M. J., Beck, T. R., and Feeney, J. A., in Corrosion Fatigue: Chemistry, Mechanics and Microstructure, NACE-2, National Association of Corrosion Engineers, 1972, p. 324.

30. Judy, R. W., Crooker, J. W., Morey, R. F., Lange, F. A., and Goode, R. J., Trans. ASM., Vol. 59, 1966, p. 195.

31. Atkinson, J. D. and Lindley, J. C., in The Influence of Environment on Fatigue, Institution of Mechanical Engineers, 1977, p. 65.

32. Wei, R. P., Talda, P. M., and Li, Che-Yu, in Fatigue Crack Propagation, ASTM STP 415, American Society for Testing and Materials, 1967, p. 460.

33. Spitzig, W. A., Talda, P. M., and Wei, R. P., Eng. Fract. Mech., Vol. 1, 1968, p. 155.

34. Dahlberg, E. P., Trans. ASM., Vol. 58, 1965, p. 46.

35. Li, C. Y., Talda, P. M., and Wei, R. P., Int. J. Fract. Mech., Vol. 3, 1967, p. 29.

36. Bamford, W. H. and Moon, D. M., "Some Mechanistic Observations on the Crack Growth Characteristics of Pressure Vessel and Piping Steels in PWR Environment," Paper 222, Int. Corrosion Forum, Atlanta, GA, March 12-16, 1979.

37. Wanhill, R. J. H., "Ambient Temperature Crack Growth in Titanium Alloys and Its Significance for Aircraft Structures," NLR MP 76008 U, March, 1976.

38. Ebara, R., Kai, T., and Inoue, K., in Corrosion-Fatigue Technology, ASTM STP 642, American Society for Testing and Materials, 1978, p. 155.

39. Duequett, D. J. and Uhlig, H.H., Trans. ASM, Vol. 62, 1969, p. 839.

40. Crooker. T. W., Bogar, F. D., and Cares, W. R., in Corrosion-Fatigue Technology, ASTM STP 642, American Society for Testing and Materials, 1978, p. 189.

41. Piper, D. E., Met. Eng. Quart., August, 1968, p. 50.

42. Barsom, J. M., "Investigation of Subcritical Crack Propagation," Ph.D. Dissertation, University of Pittsburgh, Pittsburgh, PA, 1969.

43. Barsom, J. M., in Corrosion Fatigue: Chemistry, Mechanics and Microstructure, NACE-2, National Association of Corrosion Engineers, 1972, p. 424.

44. Radon, J. C., in The Influence of Environment on Fatigue, Institution of Mechanical Engineers, 1977, p. 85.

45. Vosikovsky, O., "Frequency, Stress Ratio and Potential Effects on Fatigue Crack Growth of HY 130 Steel in Salt Water," Report MRP/PMRL-77-6(J), Canada Centre for Mineral and Energy Technology, May, 1977.

46. Vosikovsky, O., J. Eng. Mat. and Tech., ASME, Vol. 97, 1975, p. 298.

47. Scott, P. M. and Silvester, D. R. V., "The Influence of Mean Tensile Stress on Corrosion Fatigue Crack Growth in Structural Steel Immersed in Seawater," Interim Tech. Report UKOSRP 3/02, AERE, Harwell, May 25, 1977.

48. Annual Book of ASTM Standards, Designation D 1141-75, American Society for Testing and Materials, 1975, p. 48.

49. Bogar, F. D. and Crooker, T. W., "Influence of Bulk-Solution-Chemistry Conditions on Corrosion-Fatigue Crack Growth Rate," NRL Report 8265, Naval Research Laboratory, August 21, 1978.

50. Bohmer, M. and Munz, D., Z. Metallkd., Vol. 66, 1975, p. 329.

51. Hordon, M. J., Acta Met., Vol. 14, 1966, p. 1173.

52. Snowden, K. U., Acta Met., Vol. 12, 1964, p. 295.

53. Shen, S., Podlaseck, S. E., and Kramer, I. R., Acta Met., Vol. 14, 1966, p. 341.

54. Wadsworth, N. J., in Internal Stresses and Fatigue in Metals, Ed., Rasseiler, G. M. and Grube, W. L., Elsevier, Amsterdam, 1959, p. 382.

55. Wadsworth, N. J. and Hutchings, J. Phil. Mag., Vol. 3, 1958, p. 1154.

56. Ham, J. L., "Fatigue of Aluminum in Vacuum," NRC Proj. No. 42-1-0105, National Research Corporation, Cambridge, MA, 1963.

57. Grosskreutz, J. C. and Bowles, C. Q., in Environment-Sensitive Mechanical Behavior, Met. Soc. Conf., Gordon and Breach, 1965, p. 67.

58. Hudson, C., in Proc. of Vacuum Technology Conference, 1972, p. 1424.

59. Snowden, K. U. and Greenwood, J. N., Trans Met. Soc. AIME 1958, p. 626.

60. Ishii, H. and Weertman, J., Scripta Met., Vol. 3, 1969, p. 229.

61. Mautz, J. and Weiss, V., in Cracks and Fracture, ASTM STP 601, American Society for Testing and Materials, 1976, p. 154.

62. Meyn, D. A., Trans. ASM, Vol. 61, 1968, p. 52.

63. Meyn, D. A., "Fatigue Crack Propagation of Some Steels in Vacuum," NRL Report of Progress, Naval Research Laboratory, September, 1974, p. 19.

64. Irving, P. E. and Beevers, C. J., Met. Trans., Vol. 5, 1974, p. 391.

65. Floreen, S. and Kane, R. H., Met. Trans. A., Vol. 10A, 1979, p. 1745.

66. Englemaier, W., Trans. Met. Soc. AIME, Vol. 242, 1968, p. 1713.

67. Eeles, E. G. and Thurston, R. C. A., J. AIAA, Vol. 8, 1970, p. 224.

68. Eeles, E. G. and Thurston, R. C. A., J. Inst. Metals, Vol. 95, 1967, p. 111.

69. Hordon, M. J., Acta Met., Vol. 15, 1967, p. 430.

70. Wei, R. P., Pao, P. S., Hart, R. G., Weir, T. W., and Simmons, G. W., Met. Trans., Vol. 11A, 1980, p. 151.

71. Van der Sluys, W. A., J. Basic Eng., Trans. AIME, Vol. 89, 1967, p. 28.

72. Kemsley, D. M., Scripta Met., Vol. 10, 1976, p. 421.

73. Shives, T. R. and Bennett, J. A., J. Materials, Vol. 3, 1968, p. 697.

74. Johnson, H. H. and Paris, P. C., Eng. Fract. Mech., Vol. 1, 1968, p. 3.

75. Romaniv, A. N., Tkacher, V. L., and Karpenko, G. V., Fiz-Khim-Mekh-Mater, Vol. 11, 1975, p. 15.

76. Goritskii, V. M., Met. Sci. Heat. Treat., Vol. 17, 1975, p. 698.

77. Clark, W. G., Jr., in Hydrogen in Metals, Eds. Bernstein, I. M. and Thompson, A. W., American Society for Metals, 1974, p. 149.

78. Walter, R. J. and Chandler, W. T., in Effect of Hydrogen on Behavior of Materials, AIME, 1976, p. 273.

79. Ryan, N. E., in Effects of Chemical Environments on Fatigue Processes, Eds. Osborn, C. J. and Gifkins, R. C., Australian Institute of Metals, 1974, p. 221.

80. Prowse, R. L. and Wayman, M. C., Corrosion, Vol. 30, 1974, p. 280.

81. Pittinato, G. F., Met. Trans., Vol. 3, 1972, p. 235.

82. Sandoz, G., Met. Trans., Vol. 3, 1972, p. 1169.

83. Frandsen, J. D. and Marcus, H. L., Met. Trans., Vol. 8A, 1977, p. 265.

84. Hofmann, W. and Rauls, W., Weld Res. Suppl., Vol. 44, 1965, p. 225S

85. Hancock, G. G. and Johnson, H. H., Trans. AIME, Vol. 236, 1966, p. 513.

86. Hartman, A. and Schijve, J., Eng. Fract. Mech., Vol. 1, 1970, p. 615.

87. Bradshaw, F. J. and Wheeler, C., Int. J. Fract. Mech., Vol. 5, 1969, p. 255.

88. Stegman, R. L. and Shahinian, P., Met. Sci. J., Vol. 6, 1972, p. 123.

89. Duquette, D. J. and Gell, M., Met. Trans., Vol. 2, 1971, p. 1325.

90. Bradshaw, F. J. and Wheeler, C., Report No. RAE-TR-68041, 1968.

91. Wright, M. A. and Hordon, M. J., Trans. Met. Soc. AIME, Vol. 242, 1968, p. 713.

92. Stegman, R. L. and Shahinian, P., NRL Progress Report, Naval Research Laboratory, December, 1969, p. 30.

93. Ebara, R., Shibato, T., and Masumoto, I., J. Iron and Steel, Vol. 59, 1973, p. 2004.

94. Wanhill, R. J. H., Met. Trans., Vol. 7, 1976, p. 1365.

95. Walter, R. J. and Chandler, W. T., North American Rockwell Corporation, Rocketdyne, Canoga Park, CA., Reports R-7780-1, R-7780-2, R-7780-3, NASA NAS8-19, 1969.

96. Marcus, H. L., Williams, J. C. and Paton, N. E., in Corrosion Fatigue: Chemistry, Mechanics and Microstructure, NACE-2, National Association of Corrosion Engineers, 1972, p. 346.

97. Enochs, J. S. and Devereux, O. F., Met. Trans., Vol. 6A, 1975, p. 391.

98. Smith, H. H., Shahinian, P. and Achter, M. R., Trans. Met. Soc. AIME, Vol. 245, 1969, p. 947.

99. Marcus, H. L. and Stocker, P. J., AGARD-CP98, 1971, p. 16.

100. Ryder, J. T. and Gallagher, J. P., J. Basic Eng., Trans. ASME, Vol. 92, Ser. D., 1970, p. 121.

101. Gerberich, W. W., Birat, J. P., and Zackay, V. F., in Corrosion Fatigue: Chemistry, Mechanics and Microstructure, NACE-2, National Association of Corrosion Engineers, 1972, p. 396.

102. Marcus, H. L. and Sih, G. C., J. Eng. Fract. Mech., Vol. 3, 1971, p. 453.

103. Williams, D. P. and Nelson, H. G., Met. Trans., Vol. 1, 1970, p. 63.

104. Paris, P. C., Bucci, R. J., Wessel, E. T., Clark, W. G., and Mager, T. R., in Stress Analysis and Growth of Cracks, ASTM STP 513, American Society for Testing and Materials, 1972, p. 141.

105. Pook, L. P., and Greenham, A. F., in Proceedings of the Fatigue Testing and Design Conference, London, Society of Environmental Engineers, Vol. 2, April, 1976, p. 30.1.

106. Priddle, E. K., Walker, F., and Wiltshire, C., C.E.G.B. Technical Report RD/B/N3802, Berkeley Nuclear Laboratories, April, 1976.

107. Johnson, E. W. and Hill, M. L., Trans. Met. Soc. AIME, Vol. 218, 1960, p. 218.

108. Smith, H. H. and Shahinian, P., in Effects of Environment and Complex Load History on Fatigue Life, ASTM STP 462, American Society for Testing and Materials, 1970, p. 217.

109. Smith, H. H. and Shahinian, P., Trans. ASM, Vol. 62, 1969, p. 549.

110. Feeney, J. A., McMillan, J. C., and Wei, R. P., Met. Trans., Vol. 1, 1970, p. 1741.

111. Hordon, M. J. and Wright, M. A., Trans. Met. Soc. AIME, Vol. 242, 1968, p. 2011.

112. Hartman, A. and Schijve, J., Nat. Bur. Std., NLR-MP-68001-U, 1968.

113. Hutin, J. P., M.S. Thesis, Lehigh University, Bethlehem, PA, 1975.

114. Hartman, A., Jacobs, F. J., Nederveen, A., and De Rijk, R., NLR Tech. Note No. M., 1967, p. 2182.

115. Gallagher, J. P., and Sinclair, G. M., J. Basic Eng., Trans. ASME, Ser. D., Vol. 91, 1969, p. 598.

116. Pao, P. O., Wei, W., and Wei, R. P., in Environment-Sensitive Fracture of Engineering Materials, Ed. Foroulis, Z. A., The Metallurgical Society of AIME, 1979, p. 565.

117. Miller, G. A., Hudak, S. J., and Wei, R. P., J. Testing and Evaluation, Vol. 1, 1973, p. 524.

118. Hudak, S. J. and Wei, R. P., in Corrosion Fatigue: Chemistry, Mechanics and Microstructure, NACE-2, National Association of Corrosion Engineers, 1972, p. 433.

119. Meyn, D. A., NRL Progress Report, Naval Research Laboratory, 1968, p. 14.

120. Krupp, W. E., Hoeppner, D. W., and Walker, E. K., in Corrosion Fatigue: Chemistry, Mechanics and Microstructure, NACE-2, National Association of Corrosion Engineers, 1972, p. 468.

121. Bradshaw, F. J., Nunn, N. J. F., and Wheeler, C., RAE Tech. Memo MAT, 1970, p. 93.

122. Ritchie, R. O., J. Eng. Materials and Technology, Trans. ASME, Ser. H., Vol. 99, 1977, p. 195.

123. Pook, L. P., in Stress Analysis and Growth of Cracks, ASTM STP 513, American Society for Testing and Materials, 1972, p. 106.

124. Bucci, R. J., Clark, W. G., and Paris, P. C., in Stress Analysis and Growth of Cracks, ASTM STP 513, American Society for Testing and Materials, 1972, p. 177

125. Klesnil, M. and Lukas, P., Mat. Sci. and Eng., Vol. 9, 1972, p. 231.

126. Klesnil, M. and Lukas, P., Eng. Fract. Mech., Vol. 4, 1972, p. 77.

127. Priddle, E. K., C.E.G.B. Tech. Rept. RD/B/N2233, Berkeley Nuclear Laboratories, May, 1972.

128. Kitagawa, H., Nishitani, H., and Matsumoto, J., Proceedings of Third International Congress on Fracture, Munich, W. Germany, Vol. 5, April, 1973, Paper V-444/A (Verein Deutscher Eisenhuttenleute, Dusseldorf).

129. Cooke, R. J. and Beevers, C. J., Eng. Fract. Mech., Vol. 5, 1973, p. 1061.

130. Cooke, R. J. and Beevers, C. J., Mat. Sci. and Eng., Vol. 13, 1973, p. 201.

131. Otsuka, A., Mori, K., and Miyata, T., Eng. Fract. Mech., Vol. 7, 1975, p. 429.

132. Masounave, J. and Bailon, J. P., Scripta Met., Vol. 9, 1975, p. 723.

133. Masounave, J. and Bailon, J. P., Scripta Met., Vol. 10, 1976, p. 165.

134. Masounave, J. and Bailon, J. P., Proceedings of Second International Conference on Mechanical Behavior of Materials, Boston, August, 1976, p. 636.

135. Kikukawa, M., Jono, M., and Tanaka, K., Proceedings of Second International Conference on Mechanical Behavior of Materials, Boston, August, 1976, p. 716.

136. Pook, L. P., Metal Science, Vol. 11, 1977, p. 382.

137. Cooke, R. J., Irving, P. E., Booth, G. S., and Beevers, C. J., Eng. Fract. Mech., Vol. 7, 1975, p. 69.

138. Priddle, E. K., "Fracture 1977," Proceedings of Fourth International Conference on Fracture, Waterloo, Canada, June, 1977, (ed. D. M. R. Taplin), Vol. 2, p. 1249 (University of Waterloo Press).

139. Ritchie, R. O., "Fracture 1977," Proceedings of Fourth International Conference on Fracture, Waterloo, Canada, June, 1977, (ed. D. M. R. Taplin), Vol. 2, p. 1325. (University of Waterloo Press).

140. Ritchie, R. O., Met. Trans. A., Vol. 8A, 1977, p. 1131.

141. Ritchie, R. O., Metal Science, Vol. 11, 1977, p. 368.

142. Ohta, A. and Sasaki, E., Eng. Fract. Mech., Vol. 9, 1977, p. 307.

143. Robinson, J. E. and Beevers, C. J., Metal Science, Vol. 7, 1973, p. 153.

144. Robinson, J. L., Irving, P. E., and Beevers, C. J., Proceedings of Third International Congress on Fracture, Munich, West Germany, April, 1973, Vol. 5, Paper V-343 (Verein Deutscher Eisenhüttenleute, Dusseldorf).

145. Bucci, R. J., Paris, P. C., Hertzberg, R. W., Schmidt, R. A., and Anderson, A. F., in Stress Analysis and Growth of Cracks, ASTM STP 513, American Society for Testing and Materials, 1972, p. 125.

146. Irving, P. E. and Beevers, C. J., Mat. Sci. and Eng., Vol. 14, 1974, p. 229.

147. Ebara, R., Inoue, K., Crosby, S., Groeger, J., and McEvily, A. J., Proceedings of Second International Conference on Mechanical Behavior of Materials, Boston, August, 1976, p. 685.

148. McEvily, A. J. and Groeger, J., "Fracture 1977," Proceedings of Fourth International Conference on Fracture, Waterloo, Canada, June, 1977, (ed. D. M. R. Taplin), Vol. 2, p. 1293 (University of Waterloo Press).

149. Beevers, C. J., Metal Science, Vol. 11, 1977, p. 362.

150. Schmidt, R. A. and Paris, P. C., in Progress in Flaw Growth and Fracture Toughness Testing, ASTM STP 536, American Society for Testing and Materials, 1973, p. 79.

151. Knott, J. F. and Pichard, A. C., Metal Science, Vol. 11, 1977, p. 399.

152. Pickard, A. C., Ritchie, R. O., and Knott, J. F., in Proceedings of Fourth International Conference on Strength of Metals and Alloys, Nancy, France, August, 1976, p. 473.

153. Ohta, A. and Sasaki, E., Eng. Fract. Mech., Vol. 9, 1977, p. 655.

154. Von Euw, E. F. J., Hertzberg, R. W. and Roberts, R., in Stress Analysis and Growth of Cracks, ASTM STP 513, American Society for Testing and Materials, 1972, p. 230.

155. Corbly, D. M. and Packman, P. F., Eng. Fract. Mechanics, Vol. 5, 1972, p. 479.

156. Rice, R. C. and Stephens, R. I., in Progress in Flaw Growth and Fracture Toughness Testing, ASTM STP 536, American Society for Testing and Materials, 1973, p. 95.

157. Shih, T. T., "Fatigue-Crack Growth Under Variable Amplitude Loading," Ph.D. Thesis, Lehigh University, 1974.

158. Chanani, G. R., Metals Engineering Quarterly, Vol. 15, 1975, p. 40.

159. Jonas, O. and Wei, R. P., Int. J. Fract. Mechanics, Vol. 7, 1971, p. 116.

160. Probst, E. P. and Hillberry, B. M., "Fatigue Crack Delay and Arrest Due to Single Peak Tensile Overloads," AIAA Paper No. 73-325, American Institute of Aeronautics and Astronautics, March, 1973.

161. Gallagher, J. P. and Hughes, T. F., "The Influence of Yield Strength on Overload Affected Fatigue-Crack Growth Behavior in 4340 Steel," AFFDL-TR-74-28, Air Force Flight Dynamics Laboratory, 1974.

162. Schijve, J., in Fatigue-Crack Growth Under Spectrum Loads, ASTM STP 595, American Society for Testing and Materials, 1976, p. 3.

163. Schijve, J., Eng. Fract. Mech., Vol. 5, 1973, p. 269.

164. Chanani, G. R., in Corrosion Fatigue Technology, ASTM STP 642, American Society for Testing and Materials, 1973, p. 51.

165. Pelloux, R. M., in Ultrafine-Grain Metals, Syracuse University Press, Syracuse, NY, 1970, p. 231.

166. Thompson, A. W. and Bucci, R. J., Met. Trans., Vol. 4, 1973, p. 1173.

167. Thompson, A. W., Eng. Fract. Mech., Vol. 7, 1975, p. 61.

168. Hahn, H. N. and Duquette, D. J., Met. Trans. A., Vol. 10A, 1979, p. 1453.

169. Imhof, E. J. and Barsom, J. M., in Progress in Flaw Growth and Fracture Toughness Testing, ASTM STP 536, American Society for Testing and Materials, 1973, p. 182.

170. Nakasa, K., Takei, H. and Asamoto, T., J. Japan Inst. Metals, Vol. 36, 1972, p. 1180.

171. Saff, C. R., "Environment-Load Interaction Effects on Crack Growth in Landing Gear Steels," NADC-79095-60, Naval Air Development Center, December, 1980.

172. Crooker, T. W. and Lange, E. A., J. Basic Eng., Trans. ASME, Vol. 91, 1969, p. 570.

173. Gallagher, J. P., "Corrosion Fatigue Crack Growth Behavior Above and Below K_{ISCC}," NRL Report 7064, Naval Research Laboratory, Washington, D.C., May, 1970.

174. Gallagher, J. P., J. Materials, Vol. 6, 1971, p. 941.

175. Nakasa, K., Takei, H. and Asamoto, T., Trans. Japan Inst. Metals, Vol. 17, 1976, p. 726.

176. Saff, C. R. and Rosenfeld, M. S., "Load-Environment Interaction Effects on Crack Growth in Landing Gear Steels," Presented at Fourteenth Fracture Mechanics Symposium, University of California at Los Angeles, July 1, 1981, and to be published in ASTM Special Technical Publication.

177. McAdam, D. J., Jr. and Geil, G. W., Proc. ASTM, Vol. 41, 1928, p. 696.

178. Rollins, V., Arnold, B. and Lardner, E., British Corrosion J., Vol. 5, 1970, p. 33.

179. Duquette, D. J. and Uhlig, H. H., Trans. ASM, Vol. 61, 1968, p. 449.

180. Evans, U. R., The Corrosion and Oxidation of Metals, Edward Arnold Ltd., London, 1960, p. 681.

181. Brown, B. F., "Problems in Load-Carrying Application of High Strength Steels," Defense Metals Information Center, Report No. 210, 1964.

182. Tyzack, C., in Corrosion Fatigue: Chemistry, Mechanics and Microstructure, NACE-2, National Association of Corrosion Engineers, 1972, p. 379.

183. Whitwham, D. and Evans, U. R., JISI, Vol. 165, 1950, p. 76.

184. Pyle, T., Rollins, V. and Howard, D., in Corrosion Fatigue: Chemistry, Mechanics and Microstructure, NACE-2, National Association of Corrosion Engineers, 1972, p. 312.

185. Laute, K., Oberflachentech, Vol. 10, 1933, p. 281.

186. Ryabchenkov, A. V., Zhur. Fiz. Khim, Vol. 26, 1952, p. 542.

187. Finney, J. M., Mater. Sci. Eng., Vol. 6, 1970, p. 55.

188. Bradshaw, F. J., Scripta Met., Vol. 1, 1967, p. 41.

189. Simnad, M. T. and Evans, U. R., Proc. Roy. Soc., Vol. A188, 1947, p. 372.

190. Orowan, E., Nature, Vol. 154, 1944, p. 341.

191. Petch, N. J. and Stables, P., Nature, Vol. 196, 1952, p. 842.

192. Benedicks, C., Pittsburgh International Conference on Surface Reaction, 1948, p. 196.

193. Brown, T. and Nicholson, A. J., J. Inst. Metals, Vol. 89, 1960, p. 183.

194. Zapffe, C A. and Sims, C. E., Trans. AIME, Vol. 145, 1941, p. 225.

195. Troiano, A. R., Trans. ASM, Vol. 52, 1959, p. 54.

196. Beachem, C. D., Met. Trans., Vol. 3, 1972, p. 437.

197. Tetelman, A. S., in "Fracture of Solids," Eds. Drucker, D. C. and Gilman, J. J., Gordon and Breach, New York, 1963, p. 671.

198. Cotterill, P., in "Progress in Materials Science," Pergamon Press, Oxford, Vol. 9, 1961, p. 201.

199. Garofalo, F., Chou, Y. T. and Ambegaokar, V., Acta Met., Vol. 8, 1960, p. 504.

200. Bilby, B. A. and Hewett, J., Acta Met., Vol. 10, 1962, p. 587.

201. Dwyer, D. J., Simmons, G. W. and Wei, R. P., Surf. Sci., Vol. 64, 1977, p. 617.

202. Simmons, G. W., Pao, P. S., and Wei, R. P., Met. Trans. A., Vol. 9A, 1978, p. 1147.

203. Barsom, J. M., Int. J. Fract. Mech., Vol. 7, 1971, p. 163.

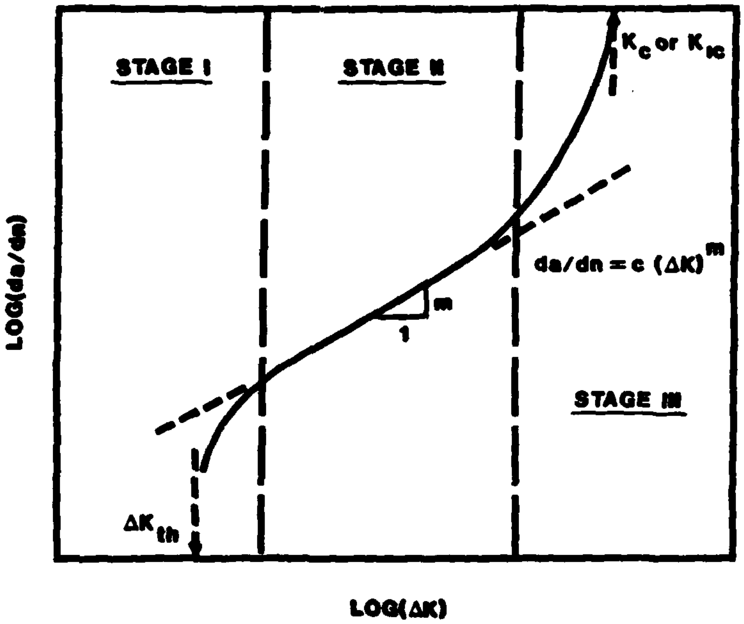


FIGURE 1. VARIATION OF FATIGUE CRACK GROWTH RATE (da/dn) WITH STRESS INTENSITY FACTOR RANGE (ΔK)

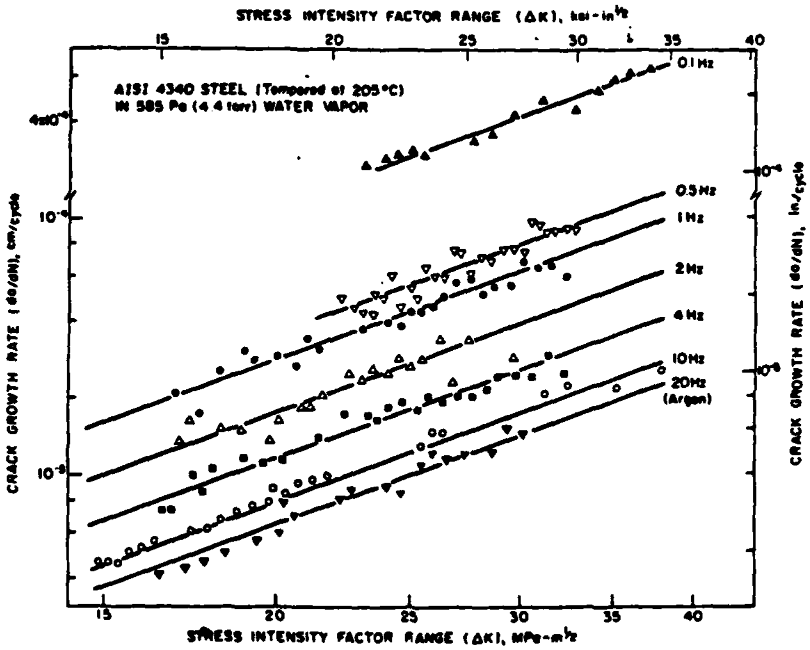


FIGURE 3. RATE VARIATION OF FATIGUE CRACK GROWTH IN 4340 STEEL WITH LOADING FREQUENCY IN DEHUMIDIFIED ARGON AND IN WATER VAPOR (BELOW K_{ISCC}) (FROM Pao, Wei, AND Wei[116])

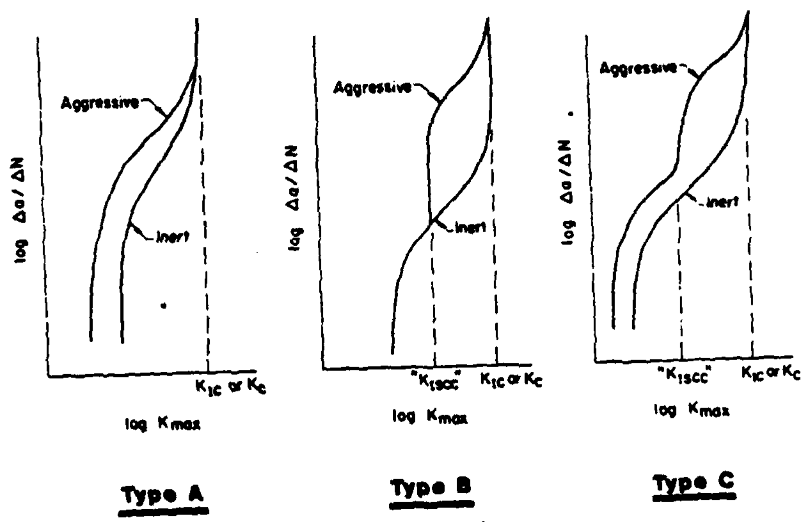


FIGURE 2. TYPES OF FATIGUE CRACK GROWTH BEHAVIOR (FROM McEvily AND Wei[16])

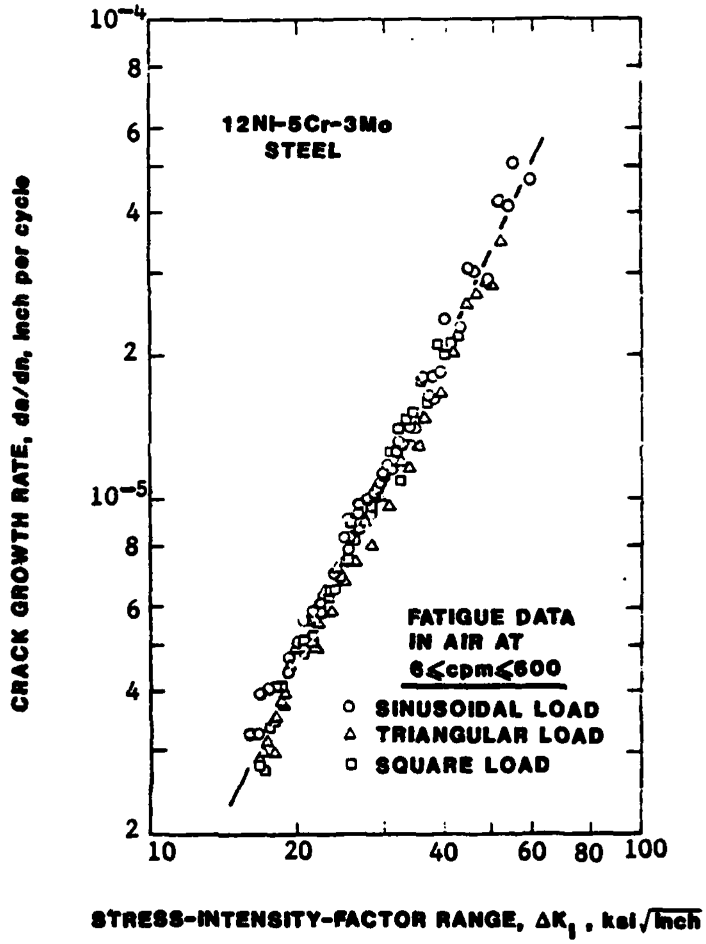


FIGURE 4. FATIGUE CRACK GROWTH RATES IN AIR UNDER SINUSOIDAL, TRIANGULAR, AND SQUARE LOADS (FROM Barsom[43])

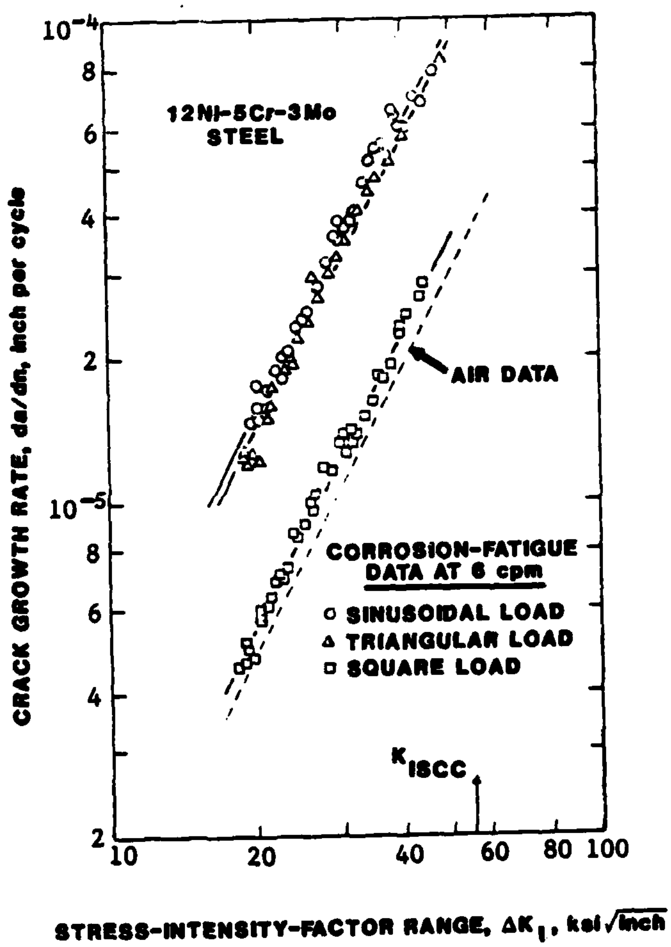


FIGURE 5. CORROSION FATIGUE CRACK GROWTH RATES BELOW K_{ISCC} UNDER SINUSOIDAL, TRIANGULAR, AND SQUARE LOADS (FROM Barsom[43])

DISTRIBUTION LIST (continued)

	No. of Copies
AFFDL, WPAFB, Ohio 45433 (Attn: FBE).	1
General Dynamics Corporation, Fort Worth, Texas 76101. .	1
Lehigh University, Bethlehem, Pennsylvania 18015 (Attn: Prof. R. P. Wei).	1
DTIC	12

DISTRIBUTION LIST

REPORT NO. NADC-81271-60

Work Unit GC129/R02208

	No. of Copies
NAVAIRSYSCOM (AIR-954)	9
2 for retention	
2 for AIR-530	
1 for AIR-320B	
1 for AIR-52032D	
1 for AIR-5302	
1 for AIR-53021	
1 for AIR-530215	
NAVSEASYSCOM, Washington, D.C. 20362.	1
NAVAIRTESTCEN, Patuxent River, Maryland	1
NAVAVNSAFECEN, NAS, Norfolk, Virginia	1
NAVSHIPRANDCEN, Bethesda, Maryland 20034.	1
NAVSHIPRANDCEN, Annapolis, Maryland 21402	1
NRL, Washington, D.C. 20375	1
NAVAIREWORKFAC, NAS, Alameda (Code 340), California	1
Jacksonville (Code 340), Florida	1
Norfolk (Code 340), Virginia	1
North Island (Code 340), California	1
Pensacola (Code 340), Florida	1
MCAS, Cherry Point (Code 340), North Carolina	1
ONR, Washington, D.C. 20362	1
USAF Systems Command, WPAFB, Ohio 45433	
(Attn: FBR)	1
(Attn: FB)	1
(Attn: LLD)	1
(Attn: FYA)	1
(Attn: LAM)	1
(Attn: FBA)	1
(Attn: LPH)	1

CONTINUED ON INSIDE COVER